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Valuation of Capabilities and System Architecture Options to Meet Affordability Requirement

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14. ABSTRACT

Weapon systems are designed for very long operational lives, which exposes them to risks of technological and operational obsolescence that can greatly shorten their expected operational life, increase their operational costs, or diminish their performance. What is needed are systems designed so that during their operational life they can be adapted to changes in their environment to continue delivering value. One way to do this is via architectural options that create the ability for a system to adapt at a relatively low cost to possible future scenarios. An architectural option is the intentional design of a system to accommodate change. The issue is that incorporation of options into a system architecture costs money and current valuation methods do not adequately evaluate the costs and benefits of these options. This paper analyzes the valuation problem of architectural options using real options theory. A problem is used to illustrate how architectural options can be defined and the method for valuation of the options to assist decision-makers in determining whether to incorporate the architectural option or not. The research contributes to performance of trade studies in acquisition through the definition of architectural options in terms consistent with defense acquisition (capabilities and not cash flows) and a theory for how program managers can value the capabilities those options provide. The research is intended to support the evolutionary acquisition of system capabilities.

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Panel 20. Enabling Affordable Programs Through Informed Early Decisions

Thursday, May 15, 2014	
3:30 p.m. – 5:00 p.m.	**Chair: Michael McGrath,** Vice President, Systems & Operations Analysis, Analytic Services Inc. ***AoAs: Toward a More Rigorous Determination of Scope*** George Thompson, Analytic Services Inc. Jaime Frittman, Analytic Services Inc. John Yuhas, Analytic Services Inc. ***Effectiveness of Competitive Prototyping and Preliminary Design Review Prior to Milestone B*** William Fast, Naval Postgraduate School ***Valuation of Capabilities and System Architecture Options to Meet Affordability Requirement*** Ronald Giachetti, Naval Postgraduate School

Valuation of System Architectural Options to Meet Affordability Requirement

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Abstract

Weapon systems are designed for very long operational lives, which exposes them to risks of technological and operational obsolescence that can greatly shorten their expected operational life, increase their operational costs, or diminish their performance. What is needed are systems designed so that during their operational life they can be adapted to changes in their environment to continue delivering value. One way to do this is via architectural options that create the ability for a system to adapt at a relatively low cost to possible future scenarios. An architectural option is the intentional design of a system to accommodate change. The issue is that incorporation of options into a system architecture costs money and current valuation methods do not adequately evaluate the costs and benefits of these options. This paper analyzes the valuation problem of architectural options using real options theory. A problem is used to illustrate how architectural options can be defined and the method for valuation of the options to assist decision-makers in determining whether to incorporate the architectural option or not. The research contributes to performance of trade studies in acquisition through the definition of architectural options in terms consistent with defense acquisition (capabilities and not cash flows) and a theory for how program managers can value the capabilities those options provide. The research is intended to support the evolutionary acquisition of system capabilities.

Introduction

The U.S. Department of Defense (DoD) acquires systems to deliver capabilities needed by the warfighter. Acquisition of a system starts with defining capability gaps and covers the system development life cycle from initial conceptualization to system production and delivery. Several challenges continue to plague the acquisition process of new systems; the adoption of a real options framework to evaluate architecture design might help address these challenges. In very complex systems for dynamic military environments, it is inevitable that user needs and operational requirements will change. While change is foreseeable, the exact nature of the change is not. The real options framework is intended to value and defend the inclusion of flexibility in system architectures to deal with uncertainty in technology and operational needs and ensure that the system delivers value to stakeholders over the span of its intended life cycle. Flexible system architectures hold out the possibility of systems that can evolve and adapt to changing operational and technical needs in order to achieve affordable programs over the long term. In this paper, we describe a framework for applying real options to value flexibility that is provided by architectural options.

This research addresses the problem of how to (1) value architectural options that deliver capabilities to the warfighter not inherently measured in dollar values, and (2) to incorporate the architectural options into a trade study of capabilities, cost, and risk to support the affordability mandate for a more effective and efficient acquisition decision-making process. The research models acquisition as a sequential decision process with an options framework but with two significant distinctions: First, it identifies and values system architectural options available in the system design, and not options on the project, and second, it measures capabilities in terms of mission effectiveness compatible with how

defense managers think. Architectural options provide flexibility to deal with technical and operational uncertainty. The research contributes to the performance of trade studies in acquisition through the definition of architectural options in terms consistent with defense acquisition (capabilities and not cash flows) and a theory for how program managers can value the capabilities those options provide. The research is intended to support the evolutionary acquisition of system capabilities.

This research project is premised on the idea that delivering affordable capabilities starts with system architecture decisions that must be part of the trade-off decisions between performance, cost, and schedule. We also observe that affordability must consider the entire service life of the system. It is probable—in fact, most existing systems have illustrated—that the needs and subsequent system requirements will change over the life of the system. For example, the IT on a ship will become obsolete and require replacement in order to maintain value. The system architecture must be designed so that these, and other less obvious changes, can be accommodated in the future; otherwise, when the architecture is not designed for these changes, the upgrades become very costly.

The systems engineering process and the acquisition process are designed to deliver systems that meet stated requirements at a particular point in time. Many designs do not accommodate for changes in the system environment in terms of threats, changes in technology, or other external changes. To make good decisions justified by the available data, the program manager needs to do the following:

- Link architectural options and decisions to needed capabilities. Achieving more or less of a particular capability usually implies a change in the system architecture, which will then in turn affect other system capabilities, including desired future capabilities.
- Deal with the uncertainty in the underlying data, model predictions, and future needs, as well as the risk that emanates from those uncertainties.
- Value capabilities in terms of mission effectiveness and performance. Normally, the units of different capabilities will be incompatible and there will be more than a few that must be simultaneously traded off, limiting the efficacy of simple two-dimensional graphs. For example, in ship design, three design parameters—displacement, endurance, and speed—must be traded off simultaneously along with other architecturally significant design parameters.
- Account for how present decisions will affect future decisions. We know that early decisions impact later system design as well as acquisition decisions. An essential characteristic of any decision support must leave flexibility—in our approach, defined as architectural options—that will accommodate future decisions affordably.

It is under uncertainty that architectural options have value. If there were no uncertainty, there would be no risk and no need for architectural options. This research subtask investigates the nature of acquisition uncertainty, risk, and capability needs and then develops a framework to model and link them together in a causal network.

Real Options

The concept of real options is taken from the financial options on which they are based. Real options allow the holder of the option to exercise the option if conditions are favorable, but the holder is not obligated to exercise the option if conditions are unfavorable (Trigeorgis, 1995). Consequently, the value of options is that they allow for the upside

potential while limiting the downside risk. Options only have value in the face of uncertainty and when that uncertainty is expected to be resolved before all of the investment decisions must be made. This situation is what is faced by advanced weapon system projects. During system development of advanced weapon systems, the uncertainty is due to technical and operational sources. Project success is only apparent after the project starts and progresses. A real options valuation considers the fact that decisions are made sequentially and that the decision-maker will use all available information at the time the decision is made.

Real options are based on the valuation of the underlying asset whose value is modeled as a stochastic process. In finance, the underlying asset is a tradeable stock and the stochastic process is an extension of the historic volatility and trend of the stock using Brownian motion. In finance, the Black-Scholes equation is used to value call and put options (Trigeorgis, 1995). For real options, selection of the underlying asset is less clear, identifying the volatility is more difficult, and there are several alternative approaches to model the stochastic process. Formulating architectural design in the context of real options allows valuation of architectural project options that in turn allows for both risk reduction and the possibility of exploiting upside potential if it should arise.

Real options give the right but not a symmetric obligation to evolve the system and enhance the opportunities for strategic growth by making future follow-on investments (e.g., case of reuse, exploring new markets, expanding the range of services while leaving the architecture intact). Since flexibility has a value under uncertainty, the value of these options lies in the enhanced flexibility to cope with uncertainty (i.e., the evolutionary changes). The importance of the real options concept cannot be overemphasized: It gives the architects/stakeholders an ability to reason about a crucial but previously intangible source of value and to factor the ability of an architecture to adapt into the tradeoff analysis and acquisition decision-making.

Real options are both a means to value investments as well as a means to define flexibility in system deployment (Trigeorgis, 2001). Koenig et al. (2009) discussed the high level of uncertainty, and hence risk, associated with conventional engineering economic analysis of projects that have long operational lives. They suggested that the DoD environment is actually rich with options, but until now, there has been no quantitative means to value them and incorporate them into the acquisition decision process. In fact, quite an extensive amount of research has been conducted on the proposed or actual use of real options with project planning and acquisition.

Real options are better at valuing investments in situations where the decision-maker has flexibility to make changes in the future and the environment is uncertain. Traditional approaches to valuing investments based on discounted cash flows are inadequate in dealing with both flexibility and uncertainty. To illustrate, consider a project to build a satellite. The investment in the satellite might be unattractive based on a pure net-present value analysis, but it may be that by launching the satellite, the organization has the opportunity to add additional valuable capabilities in the future. These possible future capabilities are not considered in the traditional value analysis, and it is these possible future capabilities, called options, that real options values. In uncertain environments when there is flexibility to make subsequent decisions, traditional valuation approaches undervalue flexibility in the system.

Related Work

This research seeks to develop a model and method to use real options to value system architectural options and is consequently related to research in system flexibility and

in real options. Flexibility has long been desired in the design of systems in order to deal with anticipated uncertainty in the system's development and operational lifetime (Giachetti, Martinez, Sáenz, and Chen, 2003; Ross, Rhodes, and Hastings, 2008). In the past decade, the theory of real options has increasingly been seen as a means to define and value flexible investment decisions in a project (Trigeorgis, 1996). Real options, inspired by the use of financial options, allow the option holder to exercise the option if conditions are favorable, but the holder is not obligated to exercise the option if conditions are unfavorable; the overall result of this process allows for upside potential and limiting the downside risk (Trigeorgis, 1996). These options have value because of the decision flexibility they provide. To date, almost all applications of real options have been what is termed options on projects (Wang & de Neufville, 2006). Typical examples include the following: Giachetti (2012) described a scenario where real options to delay, scale up, scale down, or abandon the project are applied to enterprise system projects in the DoD. Pennock, Rouse, and Kollar (2007) applied the Black-Scholes equation to ship acquisition. Angelis, Ford, and Dillard (2013) described a case study of applying real options to the Army's acquisition of the Javelin anti-tank weapon system in which they considered three alternatives to provide the capability. Real options on projects are available in all projects and have been applied in the IT industry, in the oil and gas exploration industry, and to research and development portfolios.

What is far less common is the identification and application of options in the system architecture design itself. Wang and Neufville (2006) provided an example of a real option designed into a system, where they described the design of a bridge across the Tagus River in Portugal. The bridge was being designed for automobile traffic, yet the government realized that in the future, they might want to also have trains cross the Tagus River. Building two separate bridges, one for each mode of transportation, is more expensive than if a single bridge were designed to handle both. Yet, whether rail transport would ever be realized was uncertain. The engineers proposed a real option designed into the bridge of building supports capable of supporting two decks: one for automobile traffic and a second for rail traffic. The bridge would initially be built exclusively for automobile traffic, but the beefier supports created the system architectural option for adding the second deck for rail traffic. Real options valuation lets the decision-makers analyze whether the additional investment is warranted, and in this case, it was. This example illustrates a significant difference between real options on projects versus in projects. To obtain real options in projects, the systems engineers must identify future uncertainties and design the options into the system architecture so that the option for realizing that flexibility is available in the future. The research in identifying and designing options into system architecture is far less realized than the traditional stream of research into real options (Engle & Browning, 2008). Burrman, Zhang, and Babovic (2009) examined real options and applied them to the architecture of a maritime domain protection system in which the options are defined in terms of dollar value for costs and benefits. Engel and Browning (2008) examined how to define architectural options and show a valuation scheme of mapping the standard Black-Scholes equation to terminology for modular architectures. Mohr (2009) used real options to value the flexibility of modular cabins able to accommodate changing passenger demands. Silver and de Weck (2007) used a graph to model the switching cost between different architectural configurations. Their analysis used cost. What my research has in common is that the value of the option is entirely in financial terms.

An issue in the defense sector is how to value options in terms of capabilities. Mun and Housel (2006) presented a collection of tools based on real options that uses the concept of knowledge value added (KVA) as a surrogate for the benefits derived from an option. Mun and Housel (2006) addressed the contradiction of using money to value options

for the military. Ford, Housel, and Dillard (2010) used KVA in conjunction with simulation models for the analysis of alternative unmanned aerial vehicles, and they presented data where a Predator has a KVA of 943, versus a KVA of 1222 for Sky Warrior. The question is, what do these unitless KVA values mean to an acquisition program manager? The unitless KVA measures have no correspondence to how program managers, systems engineers, and other stakeholders think about the system's performance and capabilities, which severely limits their applicability. We conclude that there is a need for valuation in terms already used within the acquisition community.

The majority of work on real options deals with options on projects, such as whether to delay, expand, contract, or make similar changes to the project dimensions. A few researchers have examined real options on the architecture, which are options designed into the architecture by engineers. Traditional options theory values the costs and benefits of options in terms of dollar values. However, military capabilities are measured in terms of MOEs and performance. A model of architectural options that delivers military capabilities needs to utilize units that have meaning to the stakeholders. Weapon system capabilities can usually not be measured in terms of money, but rather are measured in terms of MOEs.

In summary, the research on architectural options is underdeveloped, and incorporation of non-financial measures of the value of options has not been widely examined. Both these issues are critical to a more efficient acquisition process that emphasizes affordability.

Architectural Options Framework

This section describes the method I used to identify system architectural options and to value those options. Figure 1 shows the overall concept that today's capability needs will evolve over time to future capability needs. Architectural options are needed to enable fulfillment of these future capability needs. Incorporating them into the architecture today requires understanding their value—hence, real options.

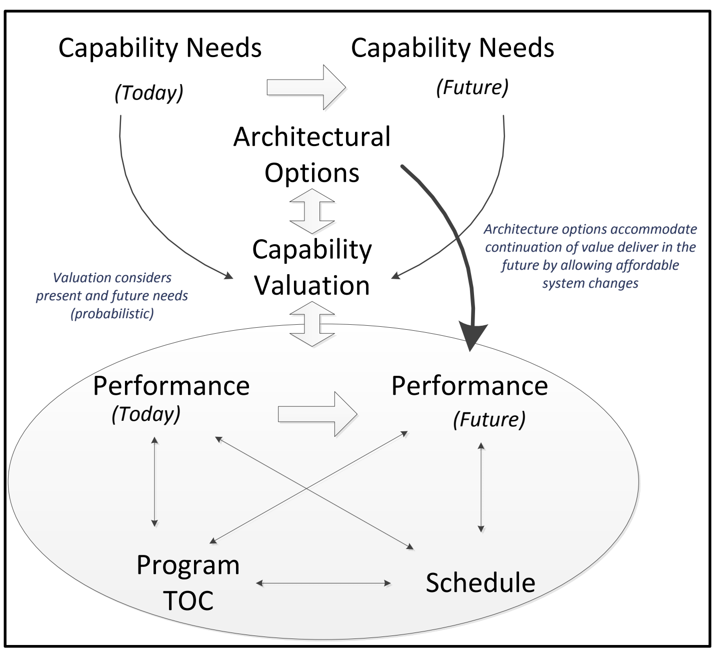

Figure 1. Architectural Options and Relationship to Capability Needs

System architecture is the representation of the structure of a system embodied by its elements, the logical and physical relationships between the elements, their relationships with the environment, and the principles or concept guiding the system's design and evolution over time. The types of elements and relationships in an architecture depend on the architectural view of operational, functional, or physical. A system architecture is divided into three main views—operational, functional, and physical architectures—with mappings showing how elements in one view are related to elements in the other views. Collectively, the three views provide a holistic model of how the system fulfills its mission. We consider all three architectural views in this research. The views are all included in Department of Defense Architectural Framework.

The development of a system architecture is driven by a design concept that gives form to ideas about how a system's functions and behaviors maximize stakeholder value. The architect must balance the many competing needs and objectives present in modern, complex system design projects. A design concept is a central part of an architecture because it describes how the system's form embodies working principles and how functions and behaviors are mapped to physical components. The concept guides future design decisions. Many acquisition professionals are familiar with operational concepts as described in the concept of operations (CONOPS) document. Likewise, design concepts underlie the functioning and physical structure of the system. Oftentimes, the architecture informally or inexplicitly defines the concept.

The architectural options approach involves the following steps:

1. identify sources of uncertainty,
2. define measures for the capabilities,
3. model uncertainty using scenarios,
4. partition the system architecture into modules,
5. define architectural options in the architecture,
6. value options, and
7. present the valuation to the decision-maker.

These steps are described in the following subsections.

Measuring Capabilities

A capability is defined as the ability to achieve a desired effect under specified standards and conditions through combinations of means and ways across DOTMLPF to perform a set of tasks to execute a specified course of action (JCIDS). The term ways and means refers to the non-materiel components and the materiel components of the capability, respectively. A capability is essentially a high-level operational requirement expressed in language that the stakeholder understands. A measure of effectiveness (MOE) is a measure that corresponds to the delivery of a capability in the system's expected environment. MOEs are defined from the stakeholder's perspective, specifically the acquirer. A good MOE is linked to the desired end state, has a strong relationship between cause and effect, and is observable and quantifiable. A MOE is defined without reference to the design solution and should in theory be a useful measure regardless of what technology, design, or process is used to meet the capability needs.

Architectural Options

The first research issue, architectural options, is part of the system design process and requires awareness of the design team to think about options as well as creativity to

design system architectures around those options. The need for architectural options in systems is to provide flexibility for the system in adapting to uncertainty in the operational and technical environment. As discussed in the Literature Review section, there is little work in identifying options in the architecture as opposed to the more common definition of options on the project.

The architectural options are all part of the same system and consequently will be interdependent—in essence, a system describes a portfolio of options. The interdependence must be included in the model since changes in any one option will affect others.

The system architectural options must be linked to the capabilities they provide and incorporated into the acquisition decision process. This entails understanding how the architectural options contribute to system performance and measuring them in a way that they can be included in the trade-off analysis conducted by the program manager and others for affordability analysis. Figure 2 shows the relationship between the sources of uncertainty, what actions could be taken to deal with the uncertainty, and how architectural options enable those actions. For example, future operations might require greater use of special operations forces, a source of operational uncertainty. A capability gap may be the Navy's ability to deploy these forces. An action could be the development of a special operations module on the Littoral Combat Ship—an "add component" action. This action is enabled by architectural options that include the infrastructure support, weight/space support, open interfaces, and ability to form modules.

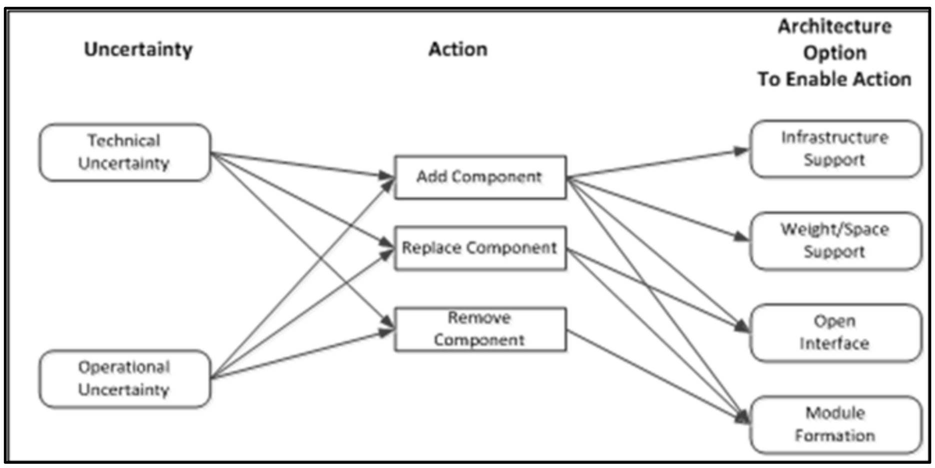

Figure 2. Relationship Between Uncertainty and Architecture Options

Illustrative Example

Figure 3 shows the Desert Patrol Vehicle (DPV), which is a high speed, lightly armored and agile land system used by military armed forces. The DPV was used successfully in the Gulf war (Operation desert storm) by the U.S. Navy Seals for rapid assaults and reconnaissance based missions. Later versions of the DPV, were known as the Light Strike Vehicles and the Advanced Light Strike Vehicle.

Figure 3. Desert Patrol Vehicle

The DPV is based on the architecture for a sand buggy. It is a rear-wheel drive on-road and off-road platform. The engine is an air-cooled Volkswagen engine with a four speed transmission. Figure 4 shows the DPV design with its weapons mounted.

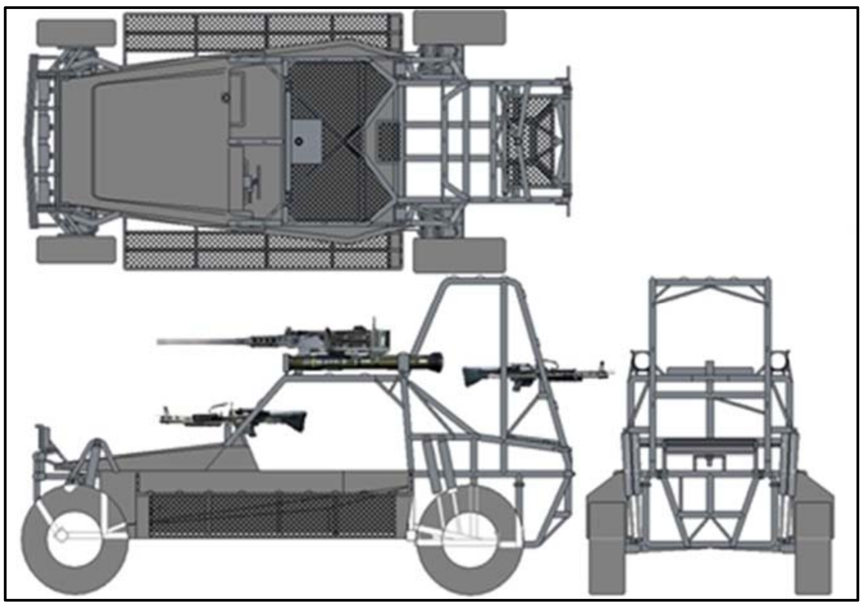

Figure 4. DPV With Weapons Mounted

The main design missions for the DPV are rapid assault and reconnaissance. The system's design mission of rapid assaults and reconnaissance leads to capability needs for mobility, payload, and survivability. MOEs that correspond to the capability needs and mission accomplishment are the three measures of maximum speed, slope, and range to measure the mobility capability. Payload capability is measured by total weight, and survivability can be measured in terms of probability to withstand a man-made as well as naturally occurring hostile environment.

I advocate the decision-maker explore the tradespace in order to understand the trade-offs between the MOEs. Figure 5 shows the trade-off between payload and range. Each point represents a single system architecture and the resulting range would be based on a simulation of that system architecture. The efficient frontier is marked with the red line, and denotes those architecture designs that are Pareto optimal. Note that the discrete points on the red line are the only feasible designs.

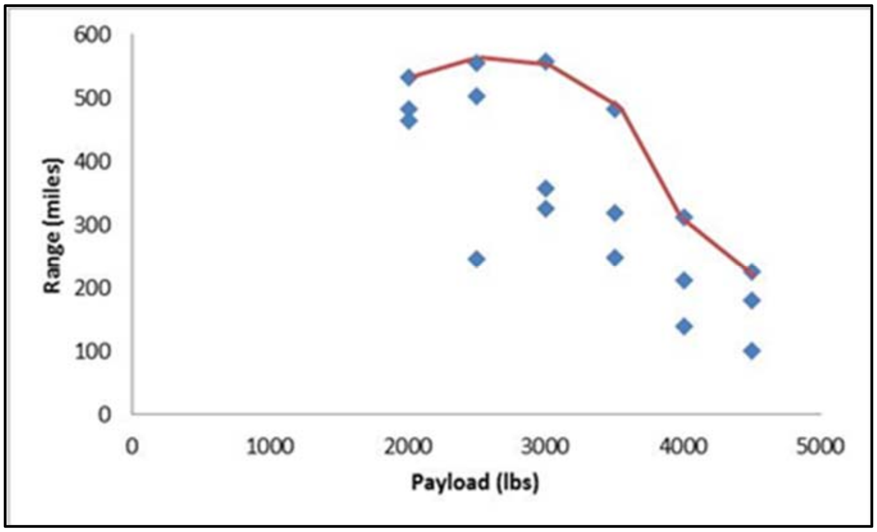

Figure 5. Tradespace for Range Versus Payload

There is often the need to aggregate the MOEs into a single measure to compare alternatives. The swing weight methodology determines the weights of each MOE based on the variation in the range of the MOE and its subjective importance as derived from stakeholders. The aggregated MOE is denoted *v(**x**)* and is given by

$$v(\mathbf{x}) = \sum_{i=1}^{n} w_i v_i(x_i) \tag{1}$$

where w_I denotes the normalized swing weight for attribute i, v_i is the value function for attribute *i* and x_i is the raw score for attribute i of candidate x. The swing weights are determined by assigning the individual MOEs to a matrix shown in Figure 6.

	importance of value measure		
variation in range	High	Medium	Low
High		survivability 10	
Medium	range 9	payload 8	
Low	Max speed 8	slope 6	

Figure 6. Matrix to Determine Swing Weights

The values in the swing weight matrix are assigned by the decision maker following the rule that values decrease from the top-left corner going right and down across the

matrix. The values are denoted by f_i and are used to calculate the swing weights by the equation

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \tag{2}$$

The MOEs can be used by the architect in conjunction with architectural heuristics to brainstorm and derive potential architectural options. The following are the options that can be identified for the DPV:

1. Flexible space for fuel, storage, personnel, or weapons
2. Space to accommodate future electronics
3. Frame design to accommodate variants (unarmored and armored)
4. Engine mounting to accommodate different engine types

To understand the nature of the design implications for an architectural options, consider the third option to design the frame to accommodate armor. The frame design must be designed stronger to carry the additional weight of the armor. The frame must include mounting and interfaces to the armor. Additionally, the overall design must be evaluated and modified for any interference issues between the armor and other components on the DPV.

An architectural option will in almost all cases have a cost associated with it. For example, the architectural option to design the structural frame to accommodate variants including an up-armored version will require additional design effort and manufacturing cost. Figure 7 illustrates how the incorporation of an option into the architecture comes at an option cost defined as the difference between a system architecture without the architectural option (Design A) and a system architecture with the architectural option (Design B). Acquisition of Architecture B allows the option that if exercised, leads to the point B+Option Exercised. The system owner would only exercise the option if the future unfolds in such a way to warrant that option. System architectures A and B are optimal for the scenario where armor is not warranted, and system architectures C and B+Option are optimal where armor is warranted.

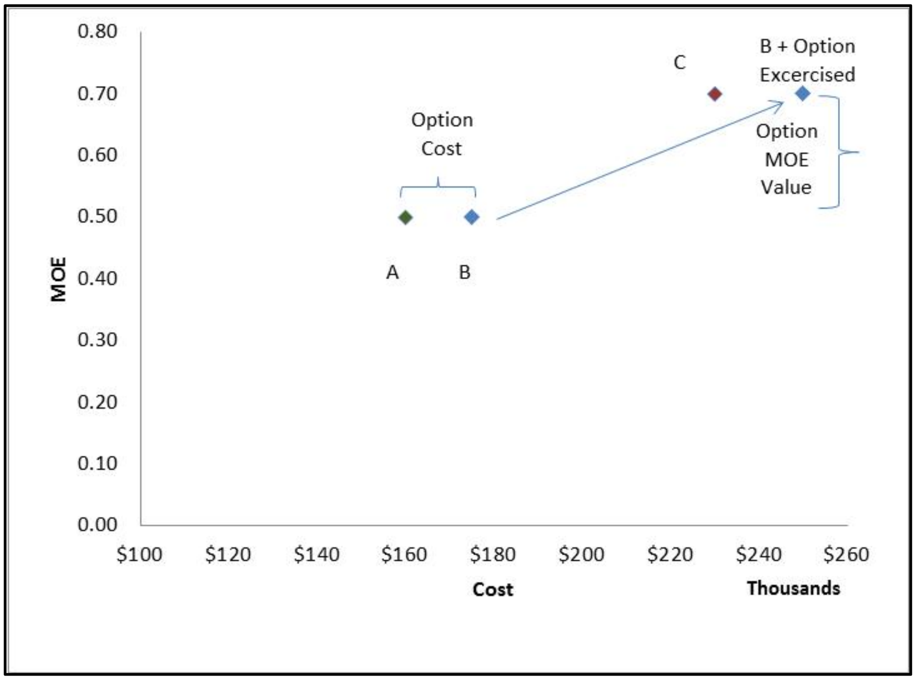

Figure 7. Option Cost and Value

Initially, referring again to Figure 7, the design team must choose between system architectures A, B, or C. Note that A and B are optimal for the current scenario without armor and if this scenario persists, then system architecture A is more cost effective than B.

In the notional example presented, the option cost is $15,000 per vehicle. The decision maker, in choosing B is paying $15,000 more for the option to add a capability later, if desired. The traditional alternative may be to go directly to C and build in the armor even if it proves unnecessary. This is a much more expensive approach when it is not used. The question is whether the possibility of needing armor justifies the option cost for B plus the cost to exercise the option. This depends on the probability of future scenarios where armor is needed. In real options theory because the future is uncertain, then the option has value. A Monte Carlo simulation of the scenarios can lead to creation of a decision matrix showing whether the option is justified by cost and under what conditions the option would be exercised.

Summary

The paper developed a method to identify and value architectural options. The approach is to identify uncertainty that the system will face, model it in a decision tree via scenarios, identify a means to measure system capabilities, define system modules and architectural options, apply real options to value the options, and then present the results to a decision-maker in the form of architecture trade-off curves. The intent of the research is to aid a decision-maker in identifying architectural options and defending their inclusion in the architectural design via the valuation.

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